Nuclear astrophysics studies with γ-ray beams: What do we expect to learn from them?

Dimiter L. Balabanski[1*]

[1]Extreme Light Infrastructure – Nuclear Physics (ELI-NP), Horia Hulubei National Institute for R&D in Physics and Nuclear Engineering, 077125 Bucharest – Magurele, Romania

Abstract. An overview of the main directions of present-day studies with quasimonochromatic γ beams is discussed with an emphasis on the research opportunities which will be offered at the Extreme Light Infrastructure Nuclear Physics (ELI-NP) facility at Magurele near Bucharest in Romania. Experiments with γ beams at the extremes of high temperatures are outlined, with an emphasis on prospective studies related to nuclear astrophysics and astroparticle physics. Some of the experimental setups for nuclear structure, reaction, and astrophysics studies, which are available at ELI-NP, are described.

1 Introduction

In a recent review [1], the status and perspectives of photonuclear research were discussed, covering both fundamental science and applications. The development of narrow-bandwidth γ beams with sufficient brilliance, based on the laser Compton backscattering (LCB) technique [2,3], made possible detailed studies of lowest-lying excitation modes in atomic nuclei, *i.e.*, $E1$, $M1$, and $E2$ excitations. In experiments with LCB γ beams [4,5], it was demonstrated that nuclear dipole response can be studied at a new level of precision and sensitivity. Thus, experiments with LCB γ beams became the ideal tool for studies of large-amplitude collective excitations in atomic nuclei, such as the isovector giant dipole resonance (IVGDR) or the pigmy dipole (PDR) resonances.

This paper focuses on prospective studies related to nuclear astrophysics and astroparticle physics at ELI-NP. The γ-beam physics program at ELI-NP has been reviewed and updated recently [6-8]. Measurements of photoneutron reaction cross sections in light nuclei address astroparticle problems such as *e.g*. studies related to ultra-high energy cosmic rays (UHECR) [9,10]. The objectives of the PANDORA project, which aims at UHECR interdisciplinary studies, are briefly summarized and the proposed photonuclear experiments are discussed. Photon-induced charged-particle reactions are related to nuclear astrophysics. The perspectives for such studies together with the instruments, which are constructed at ELI-NP, are discussed. An important development in the field is the utilization of active targets. The program for active-target experiments and the detectors, which are available or are under construction at ELI-NP, are presented. The diverse opportunities for nuclear structure

* Corresponding author: dimiter.balabanski@eli-np.ro

research with vortex photons are discussed, too. Examples of possible experiments with high orbital angular momentum (OAM) γ rays are highlighted.

2 Nuclear structure studies at high nuclear temperatures

Traditionally, photonuclear excitations were used for studies at the extreme of high nuclear temperatures. The interaction of photons with atomic nuclei is a very selective process. They induce dipole and, to a much lesser extent, quadrupole excitations due to the angular momentum selection rules. This allows investigation of dipole and quadrupole excitations over a large range of energies. Studies below and above the particle evaporation threshold are performed. In NRF experiments, it is possible to tune the quasimonochromatic γ beam such that a discrete nuclear level is excited and thus to study its decay. For details of the NRF formalism and methodology see Ref. [1]. Above the particle threshold, states in the continuum are excited. The deexcitation goes either through the emission of gamma rays, evaporation of neutrons or charged particles, or fission.

Two detector arrays were constructed at ELI-NP for such studies. The ELI-NP Array of Ge DEtectors (ELIADE) [11,12] is a dedicated detector system for NFR experiments with quasimonochromatic γ beams. It is composed of eight segmented HPGe Clover detectors, placed in the horizontal and vertical planes with respect to the beam axis, organized in two rings, at 90^0 and 135^0, correspondingly. A recent photograph of the array is presented in Figure 1a. The overall efficiency of the array is about 6%. This allows measurements of γ-ray energies, intensities, angular distributions and polarization asymmetries, as well as γγ coincidences. Thus, it will be possible to extract from the measured spectra the γ-ray branching ratios, the γ-ray multipolarities and mixing ratios, the level energies, the spins, parities, and the *K* quantum numbers of the levels, their partial and total decay widths, the transition and excitation strength, and the integrated (γ,γ′) cross-section. The performance of the ELIADE detectors was tested in-beam and the results meet the requirements for high-precision NRF experiments [13].

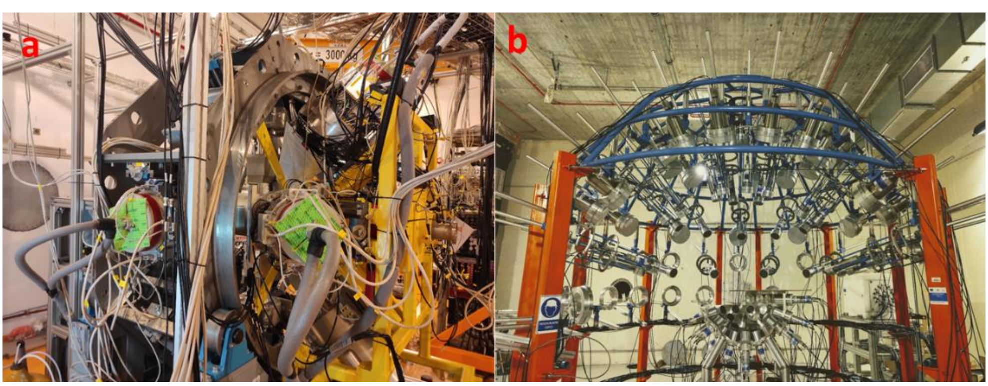

Fig. 1. (a) The ELIADE detector in the E8 experimental hall of ELI-NP, and (b) the ELIGANT-GN detector in the E9 experimental hall of ELI-NP. Photograph courtesy of Dmitry Testov (ELIADE) and Pär-Anders Söderström (ELIGANT-GN).

The family of ELI-NP Gamma Above the Neutron Threshold (ELIGANT) instruments will be used to study (γ,γ′), (γ,n), (γ,γ′n) and (γ,νn), ν = 1,2,3 reactions. Thus, photoneutron cross sections will be measured with the ELIGANT - Thermal Neutron (ELIGANT-TN) setup [14], while the ELIGANT - Gamma and Neutron (ELIGANT-GN) detector array [14,15] will be used for measurements of γ rays and neutrons emitted during the de-excitation PDR or GDR states above the particle evaporation threshold. The array, which is displayed in Figure 1b, is made of two detector assemblies, an inner one, which is placed downwards at backward angles with respect to the beam at 30 cm from the target, and an outer one, placed in the upper hemisphere at 1.5 m from the target. The inner array is used for γ-ray detection and consists of 19 $CeBr_3$ and 15 $LaBr_3$:Ce scintillation detectors. The outer array consists of 37 EJ-309 liquid scintillation detectors and 25 GS20 ^{6}Li glass detectors, and is used for the detection of neutrons. ELIGANT-GN was commissioned with radioactive sources [16] and the performance was found to correspond to the design specifications [14], as well as to the response simulations [15].

2.1 Studies of photonuclear reactions at ELI-NP

Photodisintegration is one of the basic research techniques, which will be used at ELI-NP. Experimental setups for measurements of photoneutron and charged-particle reactions were built and are ready to take the first beams, which are expected to be delivered in 2023. The experimental techniques, the observables, and the quantities, which are deduced in these experiments, were reviewed in Ref. [1]. The expected increase of the spectral density of the γ beams at the VEGA facility ELI-NP with about two orders of magnitude with respect to the current state of the art will bring the experimental techniques to a new level of sensitivity. The experimental program at the facility, which has been updated recently by Tanaka et al. [8], includes studies related to nuclear astrophysics and precise measurements of photoneutron cross sections.

Photonuclear reactions are one of the mechanisms involved in nucleosynthesis. Photons from the high-energy tail of the Plank distribution can photodisintegrate nuclei. This is demonstrated best in the synthesis of some proton-rich nuclei heavier than iron via the astrophysical *p*-process, where (γ,n), (γ,p) and (γ,α) reactions are one of the driving forces [17]. Another example, which underlines the importance of photonuclear reaction studies in astrophysics is related to studies of time-reverse reactions, such as, *e.g.*, ^{16}O(γ,α)^{12}C reaction. In this experiment, due to the low reaction cross section close to the Gamow window, a time projection chamber (TPC), with optical readout, *i.e.*, an active target, was used [18]. The experiment was recently repeated at the HIγS free-electron laser γ-ray facility at Duke University [19], using the newly developed Warsaw TPC with an electronic readout.

In active-target experiments, the target, which is a gas, serves also as a detector medium. Charged particles coming from photonuclear reactions produce drifting electrons in the active volume of the TPC. At ELI-NP, two active-target experimental setups based on the time projection chamber (TPC) technology will be available, the mini-TPC and the ELITPC [20]. The mini-TPC is available for experiments and the ELITPC is still under implementation. Both of them use an electronic readout based on the GEM detector technology [21]. The difference between the two detectors is their active volume and number of readout channels. The mini-TPC utilizes a 256-channel readout in the horizontal plane, perpendicular to the gradient of the applied voltage which forces electrons to drift. It consists of three layers of electrodes, referred to as *u-v-w* readout. They are oriented at 120^0 to each other and placed on a multilayer PCB. The ELITPC, which is a replica of the Warsaw TPC, will utilize a 1024-channel readout. The signals from the readout are processed by GET (General Electronics for TPCs) boards [22].

In addition, a 4π array of Si strip detectors, the ELI-NP Si strip detector array (ELISSA) is available for charged-particle experiments at ELI-NP [20]. It consists of 36 X3-type double-sided Si strip detectors (DSSSD), which form a barrel, and eight QQQ3-type DSSSDs, which form endcaps. The barrel is built and tested and the endcaps are still to be implemented. The total angular coverage of the instrument will be 80%, and it will detect protons of E_p = 100 keV – 10 MeV and α particles of E_α = 100 keV – 30 MeV, *e.g.* with outstanding energy and position resolution. An experimental setup, combining the X3 ELISSA DSSSD detectors in a barrel configuration with the LHASA YY2 DSSSD detectors in a lamp-shape configuration, was used for the measurement of the ^{18}F(p,α) reaction at the 3 MV tandem accelerator at IFIN-HH. The experimental setup is shown in Figure 2.

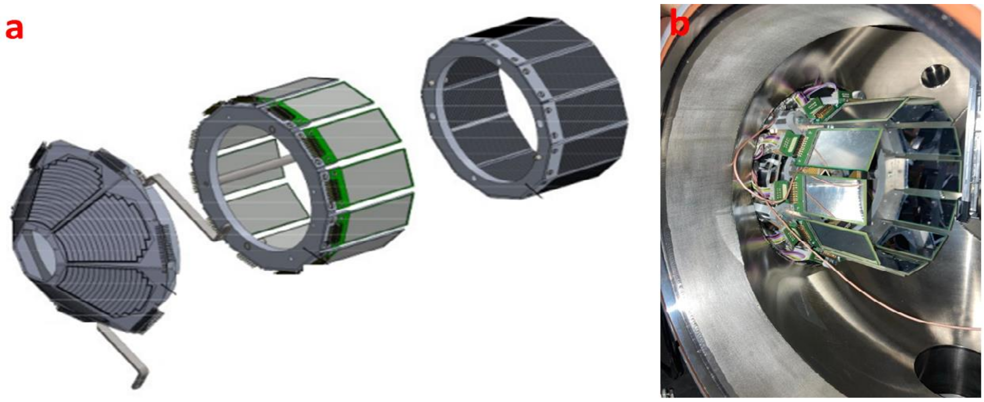

Fig. 2. (a) Schematic drawing of the ELISSA+LHASA experimental setup, and (b) the ELISSA+LHASA detector array in a reaction chamber at the 3 MV tandem accelerator of IFIN-HH. Photograph courtesy of Teodora Madgearu.

A proof-of-principle experiment was carried out at the HIγS facility, at Duke University. There the photodisintegration of ^{7}Li was studied [23], which is of importance for the understanding of the Big Bang nucleosynthesis. For this purpose, quasimonoenergetic photons in the energy range from 4.4 to 10 MeV were used, and tritons and α particles were detected in coincidence by segmented Si detectors. These studies will be continued at ELI-NP at lower energies and with better resolution in the resonance regions. Further experiments at HIγS, which will be carried out in early 2023, will include (γ,p) and (γ,α) reaction studies of the key *p*-process nuclei ^{102}Pd and ^{112}Sn.

2.2 Photonuclear reactions of light nuclei for studies of ultra-high energy cosmic rays

The PANDORA project aims to systematically measure the photonuclear response of nuclei with A ≤ 56. The experiments will be carried out at RCNP, at the University of Osaka, and iThemba Labs, Cape Town with virtual photons in (p,p′) reactions at zero degrees, and at ELI-NP with real photons.

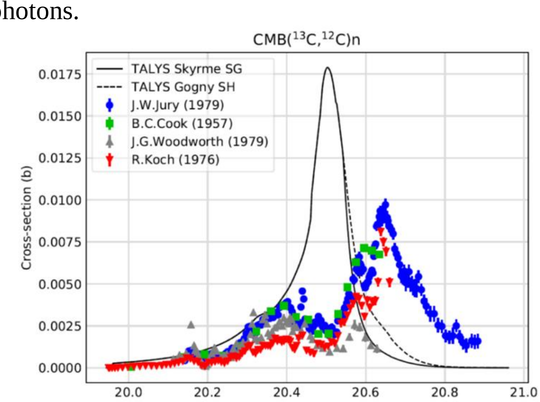

Fig. 3. Comparison of the experimental data for the cross-section of the ^{13}C(γ,n) reaction and theoretical calculations within the TALYS computer code using Skyrme and Gogny parametrizations of the level densities.

The project is of particular interest related to studies of the propagation of ultra-high energy cosmic rays (UHECR). The primary disintegration of the UHECRs in extra-galactic space is through the interaction of the particle species with the strongly Doppler-shifted cosmic microwave background leading to photonuclear reactions mainly in the GDR region. The project is carried out in synergy with the UHECR theory groups. It is intending on providing reliable photo-nuclear cross-section inputs for a large set of nuclei, which would significantly improve our understanding of the UHECR propagation and generation model. On the nuclear physics side, there is a strong need for good quality photonuclear reaction data for most of the light nuclei of astrophysical interest below iron. The situation is further complicated by the non-availability of reliable theoretical means for required photo-nuclear cross sections since the prediction of mean-field theories and statistical models do not agree well with measured values in this region, as illustrated in Figure 3 for ^{13}C. These measurements would lead to new insights into the effect of clustering, shell structure, and NN correlations on the photonuclear response of these nuclei.

The existing data for the ^{13}C(γ,n) reaction in inverse kinematics, as a function of ^{13}C kinetic energy where the cosmic microwave background serves as a target. The three facilities together will cover the full energy region of the shown data. The highest energy cosmic rays observed so far reach an energy of up to approximately $10^{20.5}$ eV. The data [24-27] demonstrate a discrepancy between themselves, but they also are off theoretical calculations which were done with the TALYS computer code [28] using Skyrme and Gogny parametrizations for the level densities.

2.3 Nuclear astrophysics with OAM photons

Astrophysics models consider also the creation of OAM photons in the Universe in the presence of strong magnetic fields [29-31]. This opens the need for revisiting a wide range of nuclear photonics problems, such as photodisintegration reactions. So far, all photodisintegration reactions were considered to be induced by normal photons, having spin 1ħ. Since there is not a single facility in the world where vortex γ rays can be generated, ongoing research is focused on theory. The modification of the photonuclear reaction cross sections in experiments with twisted photons, having angular momentum $\geq$ 2ħ, were evaluated [32], as well as the generalization of the NRF formalism for higher angular momenta of the incident photons and possible experimental applications are studied.

3 Conclusions and outlook

Photonuclear reactions attract serious interest in the understanding of a number of problems related to nuclear astrophysics and astroparticle physics. Several examples which discuss demonstrate the potential and the need for such studies. These include the understanding of the propagation of ultra-high energy cosmic rays, which requires more precise measurements of the photodisintegration reaction cross sections in light nuclei, as well as further development of the theoretical models. Other examples include studies of photonuclear reactions in active-target experiments, measurements of γ strength functions and nuclear level densities, *etc*. Such measurements will become possible with the implementation of the VEGA facility at ELI-NP. The needed equipment for the performance of these measurements is available at ELI-NP.

This work was supported by a grant from the Romanian Ministry of Research, Innovation and Digitization, CNCS – UEFISCDI, project number PN-III-P4-PCE-2021-0595, within PNCDI III program.

References

1. A. Zilges, D.L. Balabanski, N. Pietralla, J. Isaak, Prog. Part. Nucl. Phys. **122**, 103903 (2022)
2. R.H. Milburn, Phys. Rev. Lett. **10**, 75 (1963)
3. F.R. Arutyunian, V.A. Tumanian, Phys. Lett. **4**, 176 (1963)
4. H. Ohgaki, T. Noguchi, S. Sugiyama, T. Yamazaki, T. Mikado, M. Chiwaki, K. Yamada, R. Suzuki, N. Sei, Nucl. Instrum. Meth. Phys. Res. A **353**, 384 (1994)
5. N. Pietralla, Z. Berant, V.N. Litvinenko, S. Hartman, F.F. Mikhailov, I.V. Pinayev, G. Swift, M.W. Ahmed, J.H. Kelley, S.O. Nelson, R. Prior, K. Sabourov, A.P. Tonchev, H.R. Weller, Phys. Rev. Lett. **88**, 012502 (2002)
6. D.L. Balabanski, R. Popescu, D. Stutman, K. Tanaka, O. Tesileanu, C.A. Ur, D. Ursescu, N.V. Zamfir, Europhys. Lett. **117**, 28001 (2017)
7. S. Gales, K.A. Tanaka, D.L. Balabanski, F. Negoita, D. Stutman, O. Tesileanu, C.A. Ur, D. Ursescu, S. Ataman, M.O. Cernaianu, L. D'Alessi, I. Dancus, B. Diaconescu, N. Djourelov, D. Filipescu, P. Ghenuche, D.G. Ghita, C. Matei, K. Seto, M. Zeng, N.V. Zamfir, Rep. Prog. Phys. **81**, 094301 (2018)
8. K.A. Tanaka, K.M. Spohr, D.L. Balabanski, S. Balascuta, L. Capponi, M.O. Cernaianu, M. Cuciuc, A. Cucoanes, I. Dancus, A. Dhal, B. Diaconescu, D. Doria, P. Ghenuche, D.G. Ghita, S. Kisyov, V. Nastasa, J.F. Ong, F. Rotaru, D. Sangwan, P.-A. Söderström, D. Stutman, G. Suliman, O. Tesileanu, N. Tsoneva, L. Tudor, C.A. Ur, D. Ursescu, N.V. Zamfir, Matter Radiat. Extremes **5**, 024402 (2020)
9. E. Khan, S. Goriely, D. Allard, E. Parizot, T. Suomijarvi, A.J. Koning, S. Hilaire, M.C. Duijvestijn, Astropart. Phys. **23**, 191 (2005)
10. R. Alves Batista, D. Boncioli, A. di Matteo, A. van Vliet, D. Walz, J. Cosmol. Astropart. Phys. 10, 063 (2015)
11. C.A. Ur, A. Zilges, N. Pietralla, J. Beller, B. Boisdeffrw, M. Cernaianu, V. Derya, B. Löbner, C. Matei, G. Pascovici, C. Petcu, C. Romig, D. Savran, G. Suliman, E. Udup, V. Verner, Rom. Rep. Phys. **68**, S438 (2016)
12. P.-A. Söderström, G. Suliman, C.A. Ur, D. Balabanski, T. Beck, L. Capponi, A. Dhal, V. Iancu, S. Ilie, M. Iovea, A. Kusoglu, C. Petcu, N. Pietralla, G.V. Turturica, E. Udup, J. Wilhelmy, A. Zilges, Acta Phys. Pol. B **50**, 329 (2019)
13. L. Capponi, A. Kuşoğlu, P.-A. Söderström, D.L. Balabanski, G.V. Turturică, G. Bocchi, S. Chesnevskaya, A. Dhal, D. Dinescu, N. Djourelov, Y. Niu, A. Oprisa, A. Pappalardo, G. Suliman, C.A. Ur, J. Instrum. **16**, T12001 (2021)
14. F. Camera, H. Utsunomiya, D. Varlamov, D. Filipescu, V. Baran, A. Bracco, G. Colò, I. Gheorghe, T. Glodariu, C. Matei, O. Wieland, Rom. Rep. Phys. **68**, S539 (2016)
15. M. Krzysiek, F. Camera, D.M. Filipescu, H. Utsunomiya, G. Colò, I. Gheorghe, Y. Niu, Nucl. Instrum. Meth. Phys. Res. A **916**, 257 (2019)
16. Pär-Anders Söderström, Esra Açıksöz, Dimiter Balabanski, Franco Camera, Luigi Capponi, Gheorghe Ciocan, Mihai Cuciuc, Dan Filipescu, Ioana Gheorghe, Tudor Glodariu, Jasmeet Kaur, Matteus Krzysiek, Catalin Matei, Traian Roman, Adrian Rotaru, Andreea Serban, Alexandru State, Hiroaki Utsunomiya, Vlad Vasilca, Nucl. Instrum. Meth. Phys. Res. A **1027**, 166171 (2022)
17. M. Arnould, S. Goriely, Phys. Rep. **384**, 1 (2003)
18. M. Gai, D. Schweitzer, S.R. Stern, A.H. Young, R. Smith, M. Cwiok, J.S. Bihalowicz, H. Czyrkowski, R. Dabrowski, W. Dominik, A. Fijalkowska, Z. Janas, L. Janiak, A.

Korgul, T. Matulewicz, C. Mazzocchi, M. Pfuetzner, M. Zaremba, D. Balabanski, I. Gheorge, C. Matei, O. Tesilenau, V.N. Zamfir, M.W. Ahmed, S.S. Henshaw, C.R. Howell, J.M. Mueller, L.S. Myers, S. Stave, C. Sun, H.R. Weller, Y.K. Wu, A. Breskin, V. Dangendorf, K. Tittelmeier, M. Freer, Nucl. Instrum. Meth. Phys. Res. A **954**, 161779 (2020)

19. V.N. Litvinenko, B. Burnham, M. Emamian, N. Hower, J.M.J. Madey, P. Morcombe, P.G. O'Shea, S.H. Park, R. Sachtschale, K.D. Straub, G. Swift, P. Wang, Y. Wu, R.S. Canon, C.R. Howell, N.R. Roberson, E.C. Schreiber, M. Spraker, W. Tornow, H.R. Weller, I.V. Pinayev, N.G. Gavrilov, M.G. Fedotov, G.N. Kulipanov, G.Y. Kurkin, S.F. Mikhailov, V.M. Popik, A.N. Skrinsky, N.A. Vinokurov, B.E. Norum, A. Lumpkin, B. Yang, Phys. Rev. Lett. **78**, 4569 (1997)
20. O. Tesileanu, M. Gai, M. Anzalone, C. Balan, J.S. Bihalowicz, M. Cwiok, W. Dominik, S. Gales, D. G. Ghita, Z. Janos, D.P. Kendellen, M. La Cognata, C. Matei, K.Mikszuta, C. Petcu, M. Pfützner, T. Matulewicz, C. Mazzocchi, and C. Spitaleri, Rom. Rep. Phys. **68**, S699 (2016)
21. F. Sauli, Nucl. Instrum. Meth. Phys. Res. A **386**, 531 (1997); *ibid* **805**, 2 (2016)
22. E.C. Pollacco, G.F. Grinyer, F. Abu-Nimeh, T. Ahn, S. Anvar, A. Arokiaraj, Y. Ayyad, H. Baba, M. Babo, P. Baron, D. Bazin, S. Beceiro-Novo, C. Belkhiria, M. Blaizot, B. Blank, J. Bradt, G. Cardella, L. Carpenter, S. Ceruti, E. De Filippo, E. Delagnes, S. De Luca, H. De Witte, F. Druillole, B. Duclos, F. Favela, A. Fritsch, J. Giovinazzo, C. Gueye, T. Isobe, P. Hellmuth, C. Huss, B. Lachacinski, A.T. Laffoley. G. Lebertre, L. Legeard, W.G. Lynch, T. Marchi, L. Martina, C. Maugeais, W. Mittig, L. Nalpas, E.V. Pagano, J. Pancin, O. Poleshchuk, J.L. Pedroza, J. Pibernat, S. Primault, R. Raabe, B. Raine, A. Rebii, M. Renaud, T. Roger, P. Roussel-Chomaz, P. Russotto, G. Saccà, F. Saillant, P. Sizun, D. Suzuki, J.A. Swartz, A. Tizon, A. Trifiró, N. Usher, G. Wittwer, J.C. Yang, Nucl. Instrum. Meth. Phys. Res. A **887**, 81 (2018)
23. M. Munch, C. Matei, S.D. Pain, M. T. Febbraro, K. A. Chipps, H.J. Karwowski, C.Aa. Diget, A. Pappalardo, S. Chesnevskaya, G.L. Guardo, D. Walter, D.L. Balabanski, F.D. Becchetti, C.R. Brune, K.Y. Chae, J. Frost-Schenk, M.J. Kim, M.S. Kwag, M. La Cognata, D. Lattuada, R.G. Pizzone, G.G. Rapisarda, G.V. Turturica, C.A. Ur, Y. Xu, Phys. Rev. C **101**, 055801 (2020)
24. J.W. Jury, B.L. Berman, D.D. Faul, P. Meyer, K.G. McNeill, J.G. Woodworth, Phys. Rev. C **19**, 1684 (1979)
25. J.G. Woodworth, K.G. McNeill, J.W. Jury, P.D. Georgopulos, R.G. Johnson, Nucl. Phys. A **327**, 53 (1979)
26. R. Koch, H.H. Thies, Nucl. Phys. A **272**, 296 (1976)
27. Barnett C. Cook, Phys. Rev. **106**, 300 (1957)
28. A.J. Koning and D. Rochman, Nucl. Data Sheets **113**, 2841 (2012)
29. Martin Harwit, Astrophys. J. **597**, 1266 (2003)
30. Fabrizio Tamburini, Bo Thidé, Gabriel Molina-Terriza, Gabriele Anzolin, Nature Phys. **7**, 195 (2011)
31. Tomoyuki Maruyama, Takehito Hayakawa, Toshitaka Kajino, Myung-Ki Cheoun, Phys. Lett. B **826**, 136779 (2022)
32. Yi Xu, D.L. Balabanski, V. Baran, C. Matei, Phys. Rev. C, in preparation